Research Report

Atmospheric Structure and Its Variations in the Lower Thermosphere

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Abstract

COSPAR Working Group IV (International Reference Atmosphere) appointed rapporteurs to prepare reports on three altitude regions of the atmosphere for presentation at the Fourth International Space Science Symposium at Warsaw. This report is the one prepared for the intermediate altitude region (the lower thermosphere, lying between about 100 and 200 km). This region differs considerably from the lowest one, in which the volume of data makes statistical methods of analysis appropriate. For the highest region, a considerable amount of satellite data is available and the behavior of the atmosphere is reasonably well understood. Some rocket data is available for the lower thermosphere, but most of the measuring instruments are experimental and a major part of the data analysis consists in studying the physics of the various corrections or calibration factors required. At the upper end of the altitude regime some satellite data is available. New density data includes the results from flights of two types of falling spheres at Eglin AFB, Florida, results from the diffusion of chemical clouds at Woomera, Australia and Eglin AFB, and data from drag effects on three satellites with perigee altitudes near 200 km. The satellite data indicates a dependence of density on the value of the magnetic A_p index. Otherwise, the data shows more variation with the method of measurement and data reduction than actual variation of the atmosphere. Recent values of temperature include those deduced by the author from the density data and measurements by Blamont based on the broadening of the sodium and potassium resonance line and from aluminum oxide bands. Again, genuine atmospheric variations are obscured by systematic variation between the different measurement techniques. Probably the most important property of the lower thermosphere is composition. In this region there are major changes with altitude, primarily due to dissociation of oxgyen and nitrogen. The composition through out the upper atmosphere (including the exosphere) is almost entirely determined by that in the lower thermosphere. In addition to recent theoretical models, new results obtained with mass spectrometers and solar ultraviolet absorption are discussed.

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Atmospheric Structure and its Variations in the Lower Thermosphere

1. INTRODUCTION

This paper is primarily concerned with atmospheric properties in the altitude range 100 to 200 km. However, where necessary to understand the physical processes occurring in this region, or to discuss fully experimental data, results of specific measurements or calculations will be considered, even when slightly outside this altitude range. Emphasis is placed on theories and results obtained since the COSPAR International Reference Atmosphere 1961 was prepared.

2. DENSITY

For the upper part of the region with which this paper is concerned (viz. above 170 km) data is obtained from satellite observations (primarily from drag effects and at least in principle, from satellite measuring devices). Data can be obtained throughout the region from vertical rocket soundings. Unfortunately, relatively few rocket measurements have been made. Most direct measurements were made during the IGY or earlier. It is hoped that during the IQSY there will be a large scale rocket program of extensive measurements in this region.

The results of several recent measurements are as follows. Two measurements were made at Eglin Air Force Base, Florida using instrumented spheres ejected from rockets. One of these measurements was made using a newly developed expandable plastic sphere[1] (7 Dec. 1961, 1715 CST). The inflated sphere was 2.74 meters in diameter and contained three linear accelerometers mounted mutually perpendicular to each other. The total drag on the sphere was determined by vector addition of the drags measured by the individual accelerometers. Rotation of the sphere, an undesired occurrence, was also monitored from the data. Densities were measured in the altitude range of 97 to 135 km and are compared with the CIRA 1961[2] and U. S. Standard Atmospheres[3] as shown in Figure 1. Below 105 km the measured densities were higher than the models; above that altitude, densities were lower. It is difficult to be sure that these deviations are genuine or that they are due (at least in part) to inaccuracies associated with the measuring technique.

Figure 2 shows the same data compared with a representative selection of the Models of Harris and Priester[4]. The models plotted are for 0400 and 1400 hours local time (near the minimum and maximum, respectively, of the diurnal variation of density) and solar 10.7 cm wavelength fluxes of 70, 150, and 250 x 10^{-22} watts/m^2/c/s which correspond to minimum, mean, and maximum average solar flux during a solar cycle. In the altitude region of 120 to 150 km there is little variation in the density of the various Models of Harris and Priester. However, the density of these models is higher than that of the CIRA 1961 and U. S. Standard 1962, which are in good agreement with earlier measurements. Naturally, the discrepancy of the inflatable sphere data, which yielded densities lower than those of the CIRA 1961 and U. S. Standard 1962, is still greater with the Harris and Priester Models.

The second measurement was made (1 March 1962, 1207 CST) with a seven-inch aluminum sphere containing a new and improved accelerometer[5]. The accelerometer was capable of measurements down to, at least, 3×10^{-4}g. Data was obtained between 35 and 97 km, but only that above 70 km is plotted in Figure 1. Below 89 km the measured values are slightly lower than the CIRA 1961 and U. S. Standard 1962 Models. At higher altitudes the reverse is true. Both sphere measurements give densities higher than the models between 89 and 105 km. However, with data from only two measurements this may well not be significant.

Next, there are several values of density obtained from optical observations of the rate of growth of chemical releases. The data is limited to altitudes above the upper limit of atmospheric turbulence, because the effects of turbulent growth make it impossible to deduce accurate values of atmospheric parameters when such effects are present. Density points at 132 and 157 km (Figure 1) were
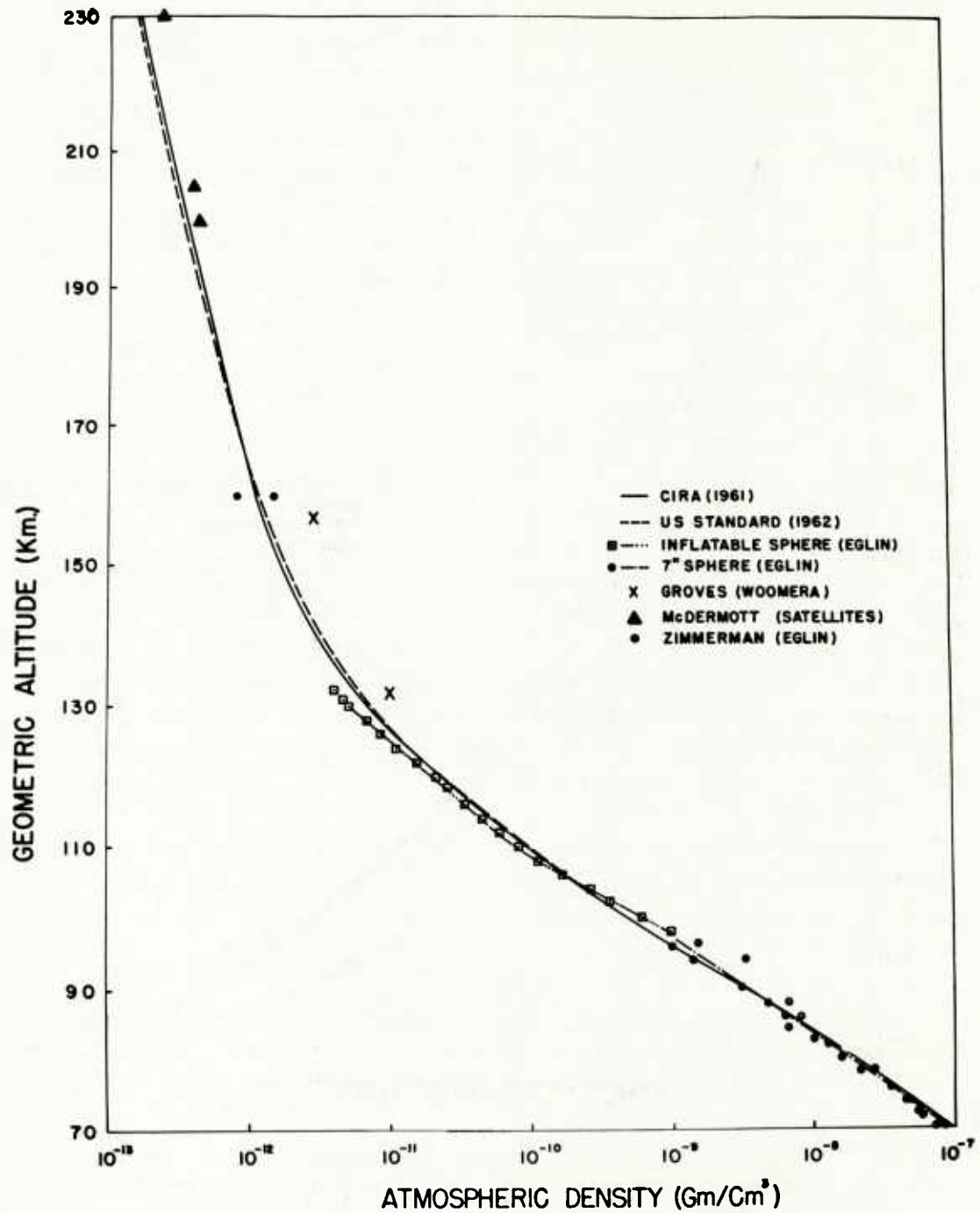
Figure 1. Density as a Function of Altitude, 70 to 230 km.
CIRA 1961, U. S. Standard Atmosphere 1962 and Recent
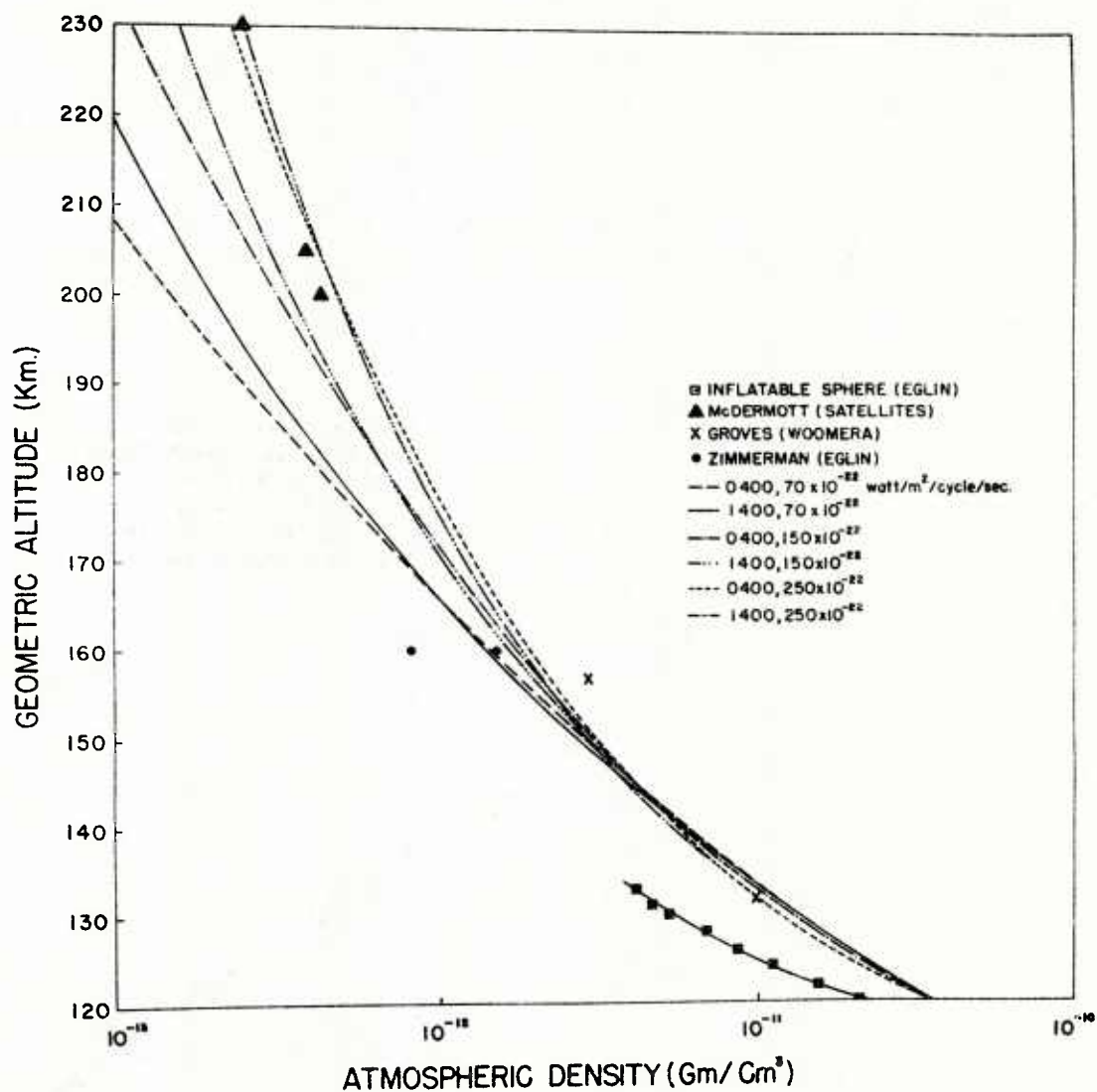Experimental Data

Figure 2. Density as a Function of Altitude, 120 to 230 km.
Harris and Priester Models for 0400 and 1400 Hours and
10.7 cm Solar Fluxes 70, 150 and 250 x 10^{-22}w/m^2/c/s
and Recent Experimental Data

calculated by Groves[6] from chemical release data obtained at Woomera at 1936 hours local time on 17 November 1960. Both densities are much higher than the models by factors of 1.6 and 2.2, respectively. The reason for this is not understood unless unusual atmospheric conditions existed over Woomera at the time. On the other hand, the density points at 160 km were calculated by Zimmerman[7] from similar data obtained at Eglin from Firefly India at 0453 CST on 1 October 1959. The chemical release consisted of a mixture of barium and sodium. If it was the diffusion of the former that was observed, a density of 8.2×10^{-13} gm/cm^3 is obtained. If sodium was observed, the density is $1.53 \times 10^{-12} gm/cm^3$. An alternative explanation is that a mean rate of diffusion existed. This would result in a density very close to that of the CIRA and U. S. Standard Models.

The above-mentioned data points have been plotted in Figure 2. Groves' density point at 132 km is in reasonable agreement with the Models of Harris and Priester, but the density at 157 km is still higher than these models. If we take the mean of Zimmerman's density points as the most likely value, a density is obtained which is lower than the models.

Between 170 and 230 km most of the recent atmospheric data has been derived by Groves or McDermott from analysis of perturbations of the orbits of U. S. satellites. McDermott[8] has studied three low altitude satellites and has derived not only mean density values, but also their dependence on the A_p magnetic index. Figure 3 shows atmospheric density at 200 km, as a function of A_p, obtained from orbital observations on 1960 o. Similarly, Figures 4 and 5 show density at 205 and 230 km, respectively, obtained from data on $1959 \epsilon 2$ and 1960μ.

If we use the empirical relation

$$\rho = \rho_O (1 + \beta Ap), \tag{1}$$

the data shown in the three figures may be summarized as follows:

Satellite	Height (km)	ρ_O (gm/cm^3)	β
1960 o	200	$(4.31 \pm 0.04) \times 10^{-13}$	$(1.86 \pm 0.7) \times 10^{-3}$
$1959 \epsilon 2$	205	$(3.9 \pm 0.1) \times 10^{-13}$	$(2.13 \pm 0.26) \times 10^{-3}$
1960μ	230	$(2.45 \pm 0.13) \times 10^{-13}$	$(3.26 \pm 0.85) \times 10^{-3}$

The values of ρ_O are plotted in Figure 1 and are 20 to 45 percent higher than the densities given by the CIRA 1961 Model. In Figure 2 they are compared with Harris and Priester's Models. The 10.7 cm solar fluxes relevant to the data are:
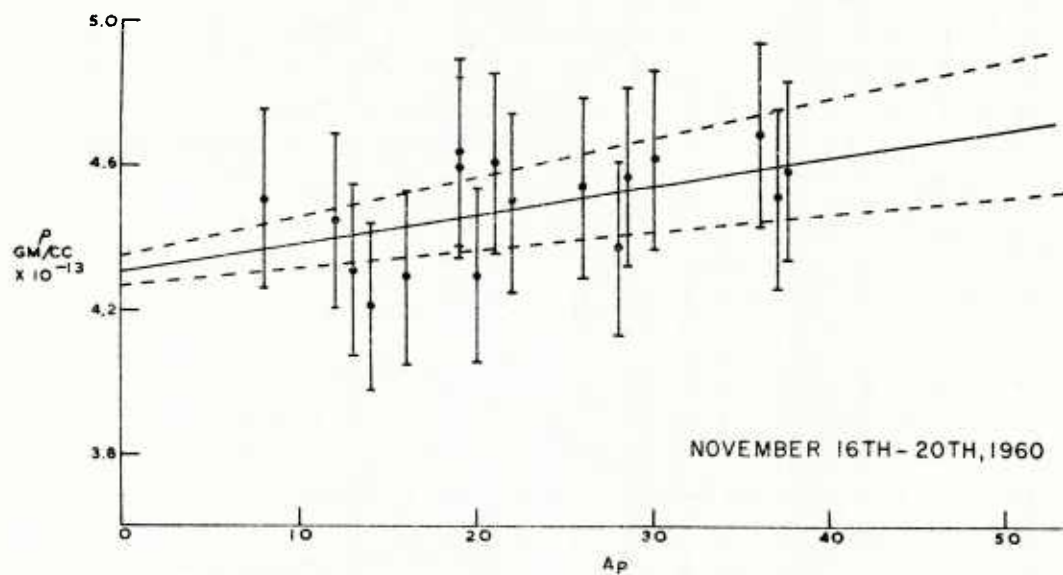
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Figure 3. Density at 200 km as a Function of A_p, Obtained by
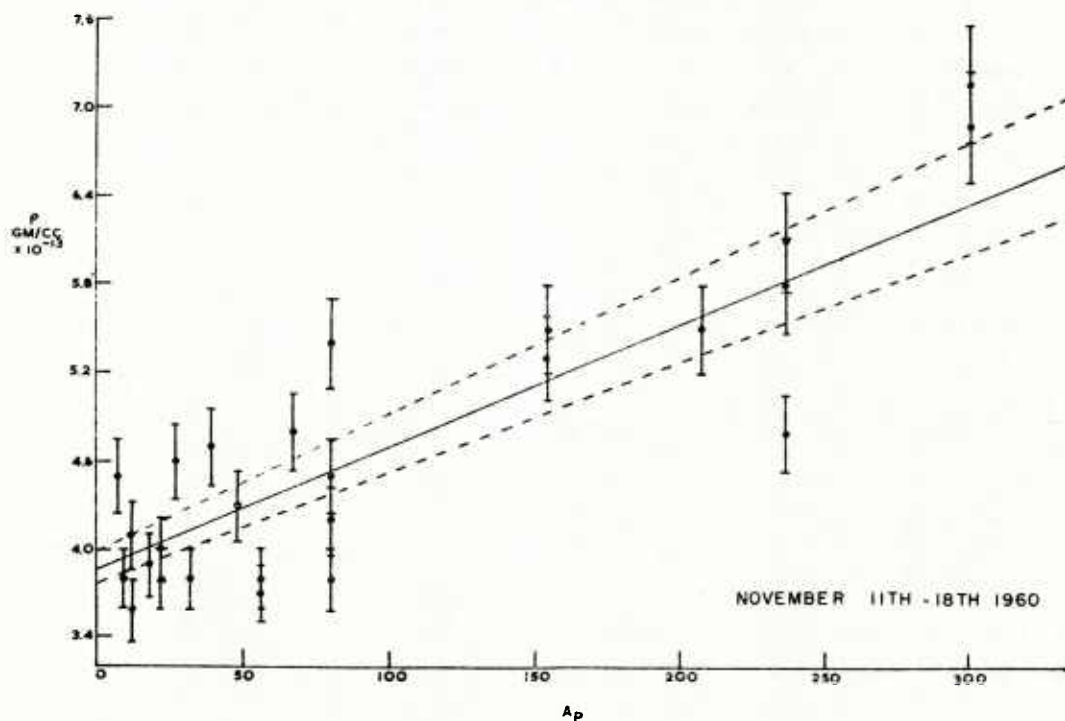McDermott from Orbital Data on 1960 o

Figure 4. Density at 205 km as a Function of A_p, Obtained by
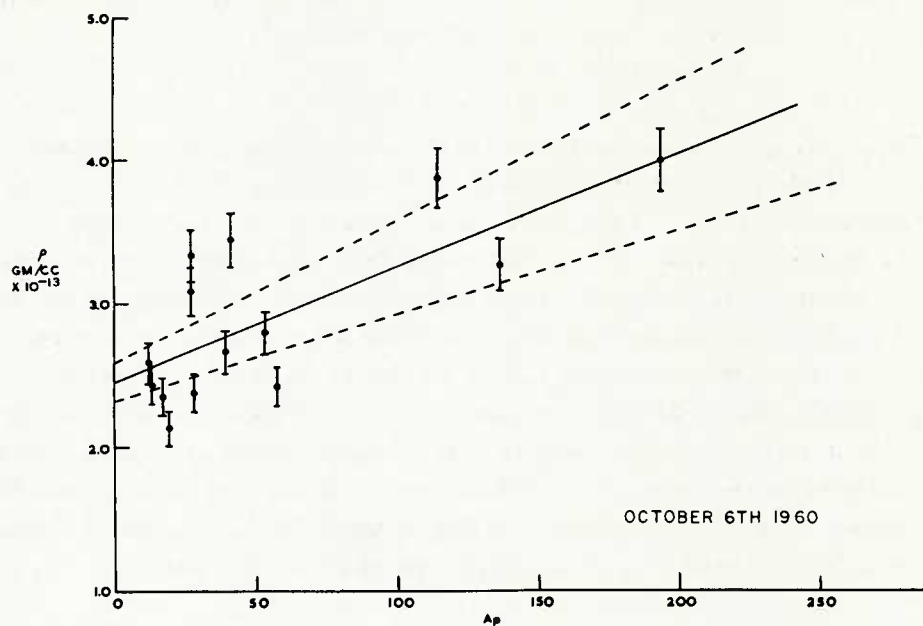McDermott from Orbital Data on 1959 ∈ 2

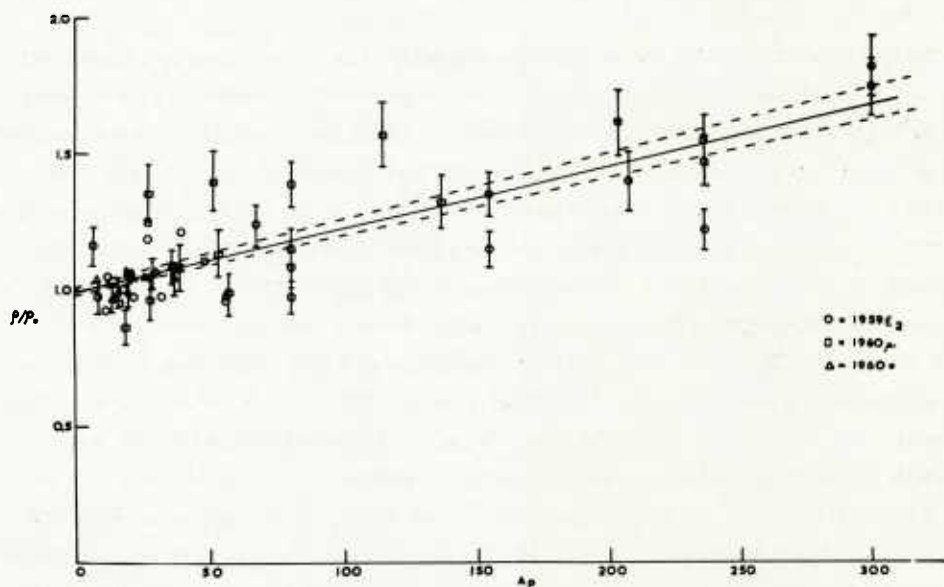Figure 5. Density at 230 km as a Function of A_p, Obtained by McDermott from Orbital Data on 1960 μ

Figure 6. Values of ρ/ρ_o, for the Data in Figures 3, 4 and 5, as a Function of A_p

Satellite	Date	Solar Flux
1960 o	16-20 Nov 1960	174 - 147 x 10^{-22} w/m^2/c/s(Mean 161)
1959 ϵ 2	11-18 Nov 1960	192 - 153 (Mean 173)
1960 μ	6 Oct 1960	132

All these density values suggest that, in the altitude region 200 to 230 km, the densities should be higher than those given by Harris and Priester.

The points in Figures 3, 4 and 5 are combined in Figure 6 and yield β = (2.4 ± 0.2) x 10^{-3} for the altitude range 200 to 230 km. Although the data is some-what scattered, the fit to a straight line is reasonably good. Recently, McDermott[8] analyzed a considerable amount of orbital data from low altitude satellites and found no correlation between density values and the 20 cm solar flux, nor any significant diurnal effect. This may be indeed so. On the other hand, it may be the result of inaccurate data, random errors in it obscuring small systematic variations. Although evidence of the correlation of atmospheric density with solar decimeter radiation below 200 km is inconclusive, at higher altitudes the relation is definite and by extrapolation downwards (if this is permissible) we find that

$$\rho \propto S^m, \tag{2}$$

where S is the solar flux intensity and values of m lying between 0.3 and 0.86 have been quoted [9,10] as applicable near 200 km. The solar flux shows a variation with a period of 27 days and this is reflected in a similar variation in the atmospheric density at higher altitudes.

Due to the rotation of the earth diurnal variations of atmospheric properties occur at most altitudes. During the day very large density increases have been detected at high altitudes (1000 km). The variations become progressively smaller at lower altitudes until, in the Models of Harris and Priester, they diminish to zero at 120 km. Harris and Priester assume that this is an isopycnic level, also independent of the solar flux. Their models indicate a diurnal variation of zero to 30 percent at 200 km and of 8 to 60 percent at 220 km. Groves, on the other hand, claims that atmospheric density decreases during the day below an isopycnic level near 200 km. His claim is based on results from low altitude U.S. satellites and were published[11] in CIRA 1961. The data was obtained during 1959-60 when the solar flux was relatively high. It is possible that there was an isopycnic level near 200 km at that time (see Harris and Priester Models for a flux of 250 x 10^{-22} w/m^2/c/s in Figure 2), but at times of lower solar flux, the level sinks to a lower altitude as predicted by the models with fluxes of 150 and 70.

There is considerable data indicating the existence of a permanent isopycnic level near 90 km (Cole[12], Groves and McDermott[13]). Diffusive separation starts

near 120 km, but it is not also an isopycnic level as assumed by Harris and Priester[4].
Thus, more accurate models might start with 90 km as an isopycnic level, with
mixing of the atmospheric constituents up to 120 km where diffusive separation
would start. Periodic variations in density with a period of six months and a
larger one with a period of one year have been detected [9,14]. These variations show
a minimum in January, a smaller minimum in July, and maxima occurring in
April and October. The magnitude of the effect is quite small in this region, being
about 10 percent between maximum and minimum. It is possible that the effect
is linked with solar corpuscular radiation which may be emitted in preferred
planes, the maxima then corresponding to motion of the earth through the planes.

3. TEMPERATURE

Recent temperature data includes the measurements of Blamont, based on
spectra of chemical releases and temperatures deduced from the density data of
McDermott, Faucher, and Faire. This data, in addition to several models, is
plotted in Figure 7. The models are the CIRA 1961[2], U. S. Standard Atmosphere[3],
and two Models of Harris and Priester[4]. The CIRA is an average model for the
entire day and medium solar activity. The U. S. Standard is a mean for the day-
light hours[15] with a solar flux of 150, which is the mean flux over a solar cycle.
The Models of Harris and Priester that are plotted are for 1900 hours local
time with a solar flux of 150 and 100, respectively. The models are reasonably
consistent, except that in the altitude region of 100-120 km, the temperature of
the U. S. Standard is slightly lower than that of the CIRA. It will be seen that this
feature and the shape of the U. S. Standard temperature curve in the 120-260 km
region is in slightly better agreement with the experimental data.

The experimental data included in Figure 7, consists of the following.
Between 70 and 96 km temperatures obtained with the seven inch falling sphere
at Eglin are in reasonable agreement with the models, but the fit is still closer
with the special winter, 30° N atmosphere developed by Court et al[16]. Between
100 and 134 km temperatures obtained from the expandable sphere are plotted.
Taking into account the solar flux (94) and the time of day (1715 hours local) when
the measurements were made, molecular temperatues (T_M) were calculated as-
suming values 540° K and 440° K, respectively, at 134.4 km. The molecular
temperature was converted into kinetic temperature (T) by means of the relation

$$T = T_M \frac{M}{M_o},$$

(3)

where M is the mean molecular weight and M_o is its value at sea level.
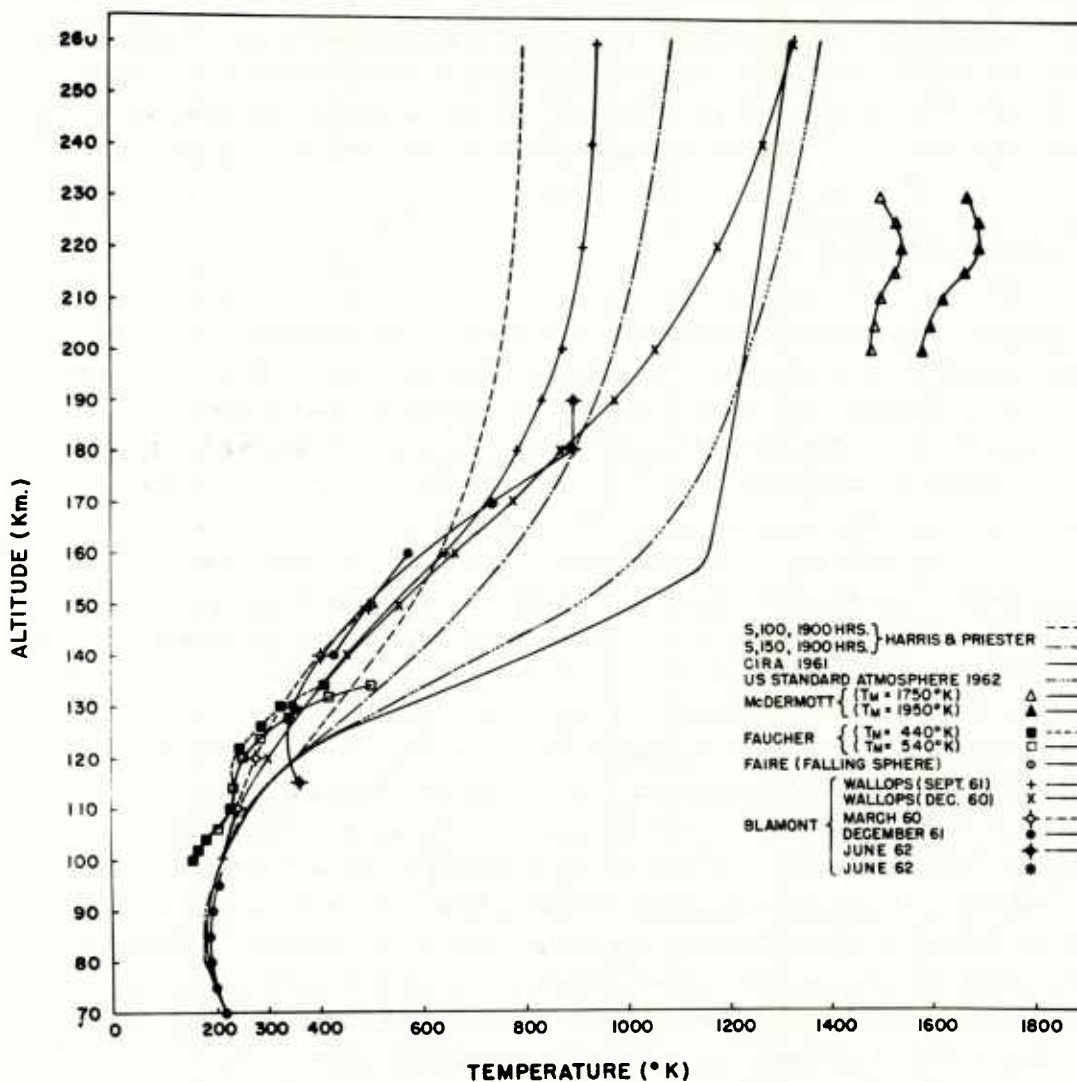
Figure 7. Kinetic Temperature as a Function of Altitude, 70 to 260 km.
CIRA 1961, U. S. Standard Atmosphere 1962, Harris and Priester
Models for 1900 Hours and 10.7 cm Solar Fluxes 100, 150 x 10^{-22}w/m^2/
c/s and Recent Experimental Data

The table of M, given in the U. S. Standard, was used for the conversion. Both temperature solutions are lower than the models, except for the initial values which are merely estimates   A change in the initial temperature has little effect on the calculated temperatures below 125 km.

Blamont has determined temperatures from the broadening of sodium and potassium resonance lines and from aluminum oxide bands. The observations were made at Colomb Bechar and Wallops Island. Although these temperature measurements are very valuable, two questions arise: (a) Since the temperature determined is appropriate to the resonance radiation emitted as a result of absorption of solar radiation, is it possible that this temperature, associated with selective absorption of solar radiation, differs from that of the ambient atmosphere? (b) Were the sodium resonance lines absorbed and re-emitted by the naturally occurring sodium in the atmosphere? This probably is not an important effect unless the chemical release is observed at an oblique angle. However, most of the naturally occurring atomic sodium lies between 80 and 100 km, which is the region of minimum temperature. Thus, if the effect is not negligible, it will result in an apparently lower temperature at the altitude of the chemical release. This effect does not apply to potassium and aluminum oxide, which can be used for comparison.

A summary of the observations is as follows:

Location	Date	Hour	Chemical	10.7 cm Solar Flux
Wallops Island	Dec. 60	$\begin{cases}0620\\1730\end{cases}$	Na(+K)	150×10^{-22} watts/m^2/c/s
	Sep. 61	$\begin{cases}0445\\1845\end{cases}$	Na(+K)	130
Colomb Bechar	Mar. 60		Na	146
	Dec. 61		K	93
	Jun. 62		K+Aℓ0	91

The two curves based on data obtained at Wallops Island are in fair agreement with the models at higher altitudes, but below 190 km the observed temperatures are low. The same is true of the March, 1960 measurement at Colomb Bechar using sodium. On the other hand, the measurements at this location using potassium and aluminum oxide are in better agreement with the models.

Finally, temperatures have been calculated (if this is permissible) from McDermott's values of ρ_0 determined from drag on satellites. As with Faucher's data, values of mean molecular weight given in the U. S. Standard Atmosphere were used to convert molecular temperature into kinetic temperature. The density values correspond to solar flux in the range of 132 to 192, with a mean value of 155. Four temperature solutions were obtained, assuming molecular temperatures of 1550, 1750, 1950, and 2150° K, respectively, at 230 km. The

kinetic temperatures corresponding to the two intermediate solutions are plotted in Figure 7. Note that the temperatures at first increase, then decrease as the altitude decreases. To eliminate this phenomenon an increase of molecular temperature at 230 km to at least 2350° K (kinetic temperature 2002°K) would be required. The significance of the resulting temperatures is not clear.

The foregoing discussion indicates the problem. The data of Blamont and Faucher give temperatures and densities lower than the models in the altitude region 100 to 190 km. On the other hand, Groves and McDermott's data from chemical releases and satellite drag yield densities higher than the models in the interval of 130 to 230 km. This data also implies a larger scale height (or temperature) in this region.

Some electron temperatures measured in the ionosphere were considerably higher than neutral gas temperatures given in model atmospheres. In some ways, this is analogous to the observation in laboratory gas discharges that electrons have higher temperatures than the gas, except at relatively high pressures. Dalgarno[17] has calculated electron temperatures expected in the upper atmosphere. Below 120 km and above 400 km he finds no significant difference between the electron and gas temperature. Between 120 and 400 km however, he finds electron temperatures considerably in excess of gas temperatures. The maximum difference may be as high as 1500°K and occurs at an altitude near 200 km.

4. COMPOSITION

Determination of the composition of the upper atmosphere is a difficult task. For this reason there is not a large amount of data and there is a wide variation in the data that is available. Measurements are made with mass spectrometers or of the absorption of solar ultraviolet radiation. The latter technique, in principle, is the more accurate, since vehicle contamination effects are not important, but it is hampered at present by lack of precision of the absorption cross-sections of the individual constituents. The technique is also restricted to that portion of a day when the solar angle with the zenith is not too large. Vehicle and instrumentation failures have plagued many mass spectrometer measurements, but even when good values of the ion currents due to the various species have been obtained, many questions have to be answered. Some of these questions are the following: One is the effect of flight dynamics on the gas sampling. This is primarily important if the absolute number densities of the various species are to be derived from the observations, but also, under some conditions the relative number densities of the gas species in the spectrometer may not be the same as in the ambient. Another question is the effect of gas carried with the rocket, namely, entrained air and gases from the rocket fuel. The

magnitude of this contamination will vary from one experimental design to another. The sensitivity of the spectrometer is not the same for all masses. For example, a quadrupole massenfilter is usually more sensitive to light masses than to heavy masses. On the other hand, recent measurements of the argon/molecular nitrogen ratio by Cohen[18] may imply that a time-of-flight spectrometer is more sensitive to heavy masses. Finally, 0^+ produced in the ion source can be lost by charge transfer with molecular oxygen (in which case it may appear in the spectrometer as 0_2^+) or by recombination on surfaces of the instrument.

After a long period of development, Schaefer[19] has obtained good mass spectrometer measurements of the neutral constituents of the atmosphere. The measurement was made with a Nike-Cajun rocket launched at 1302 EST, May 18, 1962. The measuring instrument was a massenfilter mounted in an ejectable unit which contained its own ion source and telemetry system. So that the effect of rocket-borne contaminants were minimized, the system was initially pressurized with helium and then ejected from the rocket before measurements were made. The ion source was designed in the form of an open "squirrel-cage" so as to minimize surface recombination. The $0/0_2$ current ratio is plotted in Figure 8. This plot requires the use of a calibration factor to convert it into the ratio of $0/0_2$ ambient density. However, the factor probably does not differ greatly from unity. Recently, Schaefer[20] has repeated the preceding measurement using two Nike-Apache rockets which reached peak altitudes of approximately 190 km. Preliminary results of one flight, at 0300 hours EST, 28 March 1963 suggest that the 0 ion current is nearly equal to the N_2 ion current and that 0_2 is negligible at 190 km.

At 1500 hours MST, 6 March 1963, Cohen[18] fired an Aerobee rocket at White Sands, New Mexico equipped with a time-of-flight mass spectrometer. Densities of 0, 0_2, N_2, and A were measured in the altitude region of 153 to 203 km. Preliminary values of the $0/0_2$ current ratio are plotted in Figure 9. These values suggest less oxygen dissociation than does the data of Schaefer. However, Narcisi and Cohen believe that when the calibration factor appropriate to their instrument is applied, most of this difference will disappear.

Figure 10 shows plots of number densities of neutral 0, 0_2, and N_2 as a function of altitude deduced by Hinteregger[21] from data obtained with a rocket flight containing a monochromator at 1005 hours MST, 23 August 1961. The 10.7 cm solar flux on that date was 98×10^{-22} $w/m^2/c/s$. The ratios of the particle number densities at 200 km, shown in the figure, to those of Harris and Priester for the same solar flux and time of day are: 0 5.0, 0_2 1.24, N_2 0.40-total number, 2.24. The corresponding ratios at 120 km are: 0 3.3, 0_2 0.14, N_2 0.31 - total number, 0.55. The kinetic temperatures of Hinteregger and Priester in this range are approximately the same. For example, at 200 km they are $825^{\circ}K$ and $813^{\circ}K$, respectively. Bearing this in mind, there are
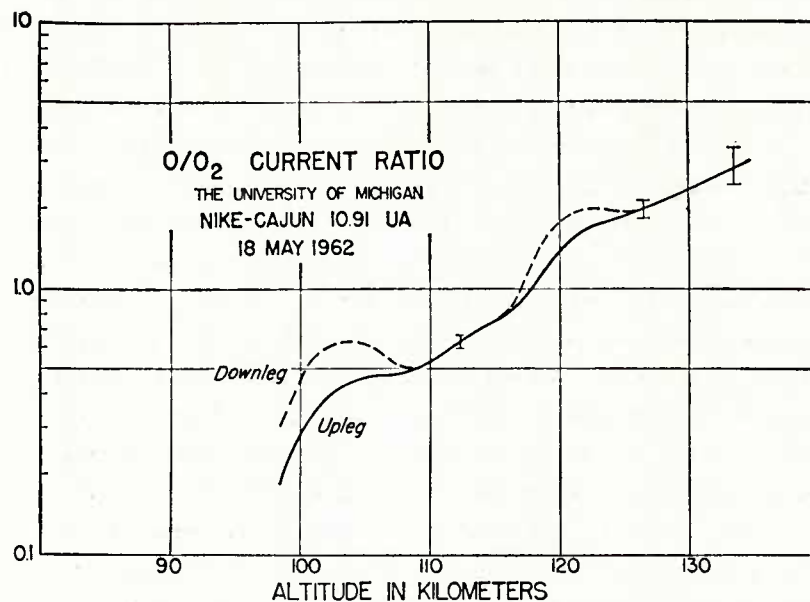
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Figure 8. O/O_2 Ion Current Ratio as a Function of
Altitude, Measured by Schaefer at Wallops Island,
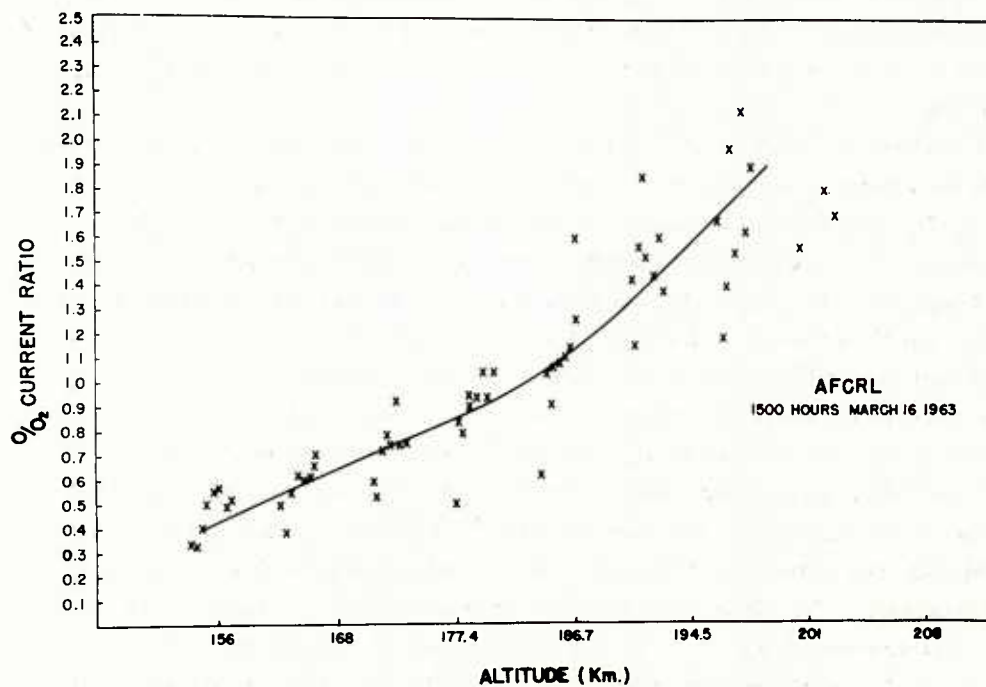1302 EST, 18 May 1962

Figure 9. O/O_2 Ion Current Ratio as a Function of Altitude, Measured
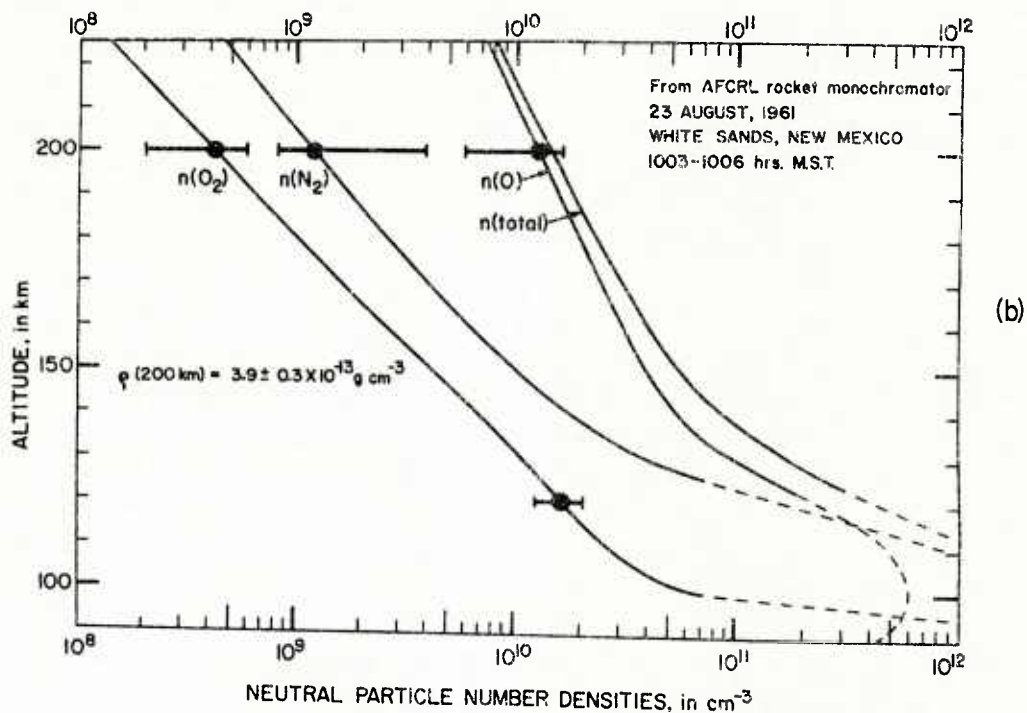by Cohen et al, at White Sands, 1500 MST, 6 March 1963

Figure 10. Number Densities of O, O_2 and N_2 as a function of Altitude Deduced by Hinteregger from Ultraviolet Absorption Data Obtained at White Sands, 1005 MST, 23 August 1961
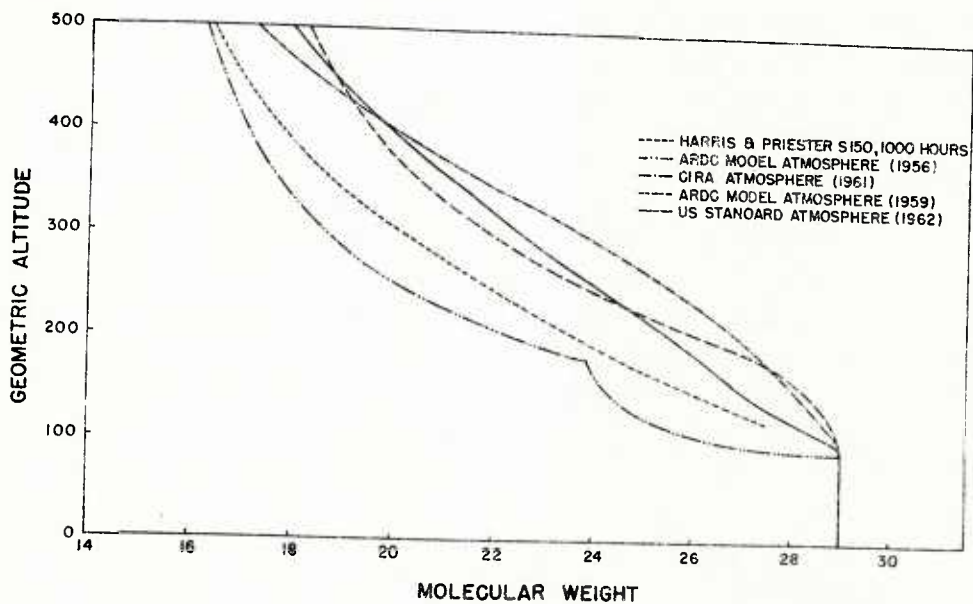

Figure 11. Mean Molecular Weight as a Function of Altitude, ARDC Model 1956, ARDC Model 1959, CIRA 1961, U. S. Standard Atmosphere, 1962, Harris and Priester 1000 hours, Solar Flux 150 x 10^{-22} w/m^2/c/s

some obvious discrepancies in the variation with altitude of the ratios given above.
This is particularly marked with O_2, which has a ratio of 1.24 at 200 km and 0.14
at 120 km. It is tempting to hypothesize that the former value is accurate and that
Hinteregger's O_2 density at 120 km should be increased by a factor of about 9, with
a resultant decrease in 0 density at all altitudes considered. Hinteregger's data
would then be in good agreement with other data. Nicolet[22], in discussing the same
data, also concludes that the mean molecular weight that it yields (about 18 at
200 km) is too low.

Two other measurements yield information that is of considerable value in
our understanding of the composition of the upper atmosphere and its variations.
The first is the measurement of the O_2 concentration as a function of altitude,
using ultraviolet radiation detectors on a rocket, by Kupperian et al[23]. Although
these measurements were made during the IGY, their significance is still im-
portant. The dissociation level was found to vary at Churchill from about 86 km
in mid-summer (1957) to 96 km in early spring (1958). This variation is probably
due to the seasonal change in average solar elevation at this location. The dis-
sociation level is probably also a function of other parameters - for example, time
of day and solar flux. Thus, it is not justifiable to assume that the composition at,
say, 120 km is invariant.

Finally, the altitude at which diffusive separation starts is not constant. This
altitude has frequently been assumed to be 120 km, but the actual altitude must
show frequent variations. It may vary in a systematic way with such parameters
as time of day but, in addition, diffusive separation does not take place in the
presence of turbulence and this may occur at a given altitude merely as a result
of a particular wind-shear pattern. Nevertheless, the lower limit of diffusive
separation appears to normally lie between 110 and 120 km. Diffusive separation
has been studied extensively by Meadows-Reed et al[24]. A summary of some of
the data on the altitude of diffusive separation is as follows:

Date	Hour	Altitude of Separation	Observer
Sept. 9, 1960	2400*	105-110 km	Pokhunkov[25]
Nov.20, 1956	2320	~105	Meadows and Townsend
Feb.21, 1958	2000	112} Churchill	
Mar.22, 1958	1207	119	
Nov. 15, 1960	1140	111 Wallops	

* all times are local.

In Figure 11 are plotted values of mean molecular weight, as a function of
altitude, that have been used in several model atmospheres. It is generally
agreed that between sea level and 90 km the mean molecular weight remains

virtually constant. At higher altitudes the value depends on the degree of dissociation, the altitude of diffusive separation and the values of temperature in the region of diffusive separation. The temperature is a function of time of day and solar flux and is known reasonably accurately. The altitude of diffusive separation varies in a relatively random manner. The variation of the degree of dissociation at the altitude of diffusive separation is not known, but it probably is a function of solar (ultraviolet) flux[15] and possibly, also of time of day and latitude[23].

NOTE: In general, recent USSR data on the upper atmosphere is not included in this review but is to be reported separately.

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behavior of the atmosphere is reasonably well understood. Some rocket data is available for the lower thermosphere, but most of the measuring instruments are experimental and a major part of the data analysis consists in studying the physics of the various corrections or calibration factors required. At the upper end of the altitude regime some satellite data is available. New density data includes the results from flights of two types of falling spheres at Eglin AFB, Florida, results from the diffusion of chemical clouds at Woomera, Australia and Eglin AFB, and data from drag effects on three satellites with perigee altitudes near 200 km. The satellite data indicates a dependence of density on the value of the magnetic Ap index. Otherwise, the data shows more variation with the method of measurement and data reduction than actual variation of the atmosphere. Recent values of temperature include those deduced by the author from the density data and measurements by Blamont based on the broadening of the sodium and potassium resonance lines and from aluminum oxide bands. Again, genuine atmospheric variations are obscured by systematic variations between the different measurement techniques. Probably the most important property of the lower thermosphere is composition. In this region there are major changes with altitude, primarily due to dissociation of oxygen and nitrogen. The composition throughout the upper atmosphere (including the exosphere) is almost entirely determined by that in the lower thermosphere. In addition to recent theoretical models, new results obtained with mass spectrometers and solar ultraviolet absorption are discussed.